

Residential Electricity Demand in China –Can Efficiency Reverse the Growth?

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Abstract

The time when energy-related carbon emissions come overwhelmingly from developed countries is coming to a close. China has already overtaken the United States as the world's leading emitter of greenhouse gas emissions. The economic growth that China has experienced is not expected to slow down significantly in the long term, which implies continued massive growth in energy demand. This paper draws on the extensive expertise from the China Energy Group at LBNL on forecasting energy consumption in China, but adds to it by exploring the dynamics of demand growth for electricity in the residential sector – and the realistic potential for coping with it through efficiency.

This paper forecasts ownership growth of each product using econometric modeling, in combination with historical trends in China. The products considered (refrigerators, air conditioners, fans, washing machines, lighting, standby power, space heaters, and water heating) account for 90% of household electricity consumption in China.

Using this method, we determine the trend and dynamics of demand growth and its dependence on macroeconomic drivers at a level of detail not accessible by models of a more aggregate nature. In addition, we present scenarios for reducing residential consumption through efficiency measures defined at the product level. The research takes advantage of an analytical framework developed by LBNL (BUENAS) which integrates end use technology parameters into demand forecasting and stock accounting to produce detailed efficiency scenarios, thus allowing for a technologically realistic assessment of efficiency opportunities specifically in the Chinese context.

Introduction

China's energy consumption has been the focus of the China Energy Group at LBNL for more than two decades. Building on their extensive expertise on the subject, this paper presents a driver based bottom-up methodology that allows the modelers to predict China future energy consumption to 2050, and to investigate several energy efficiency scenarios. This paper focuses on residential electricity only with the study of the following end-uses: lighting, standby power, refrigerators, air conditioners, fans, washing machines, water heaters and space heaters.

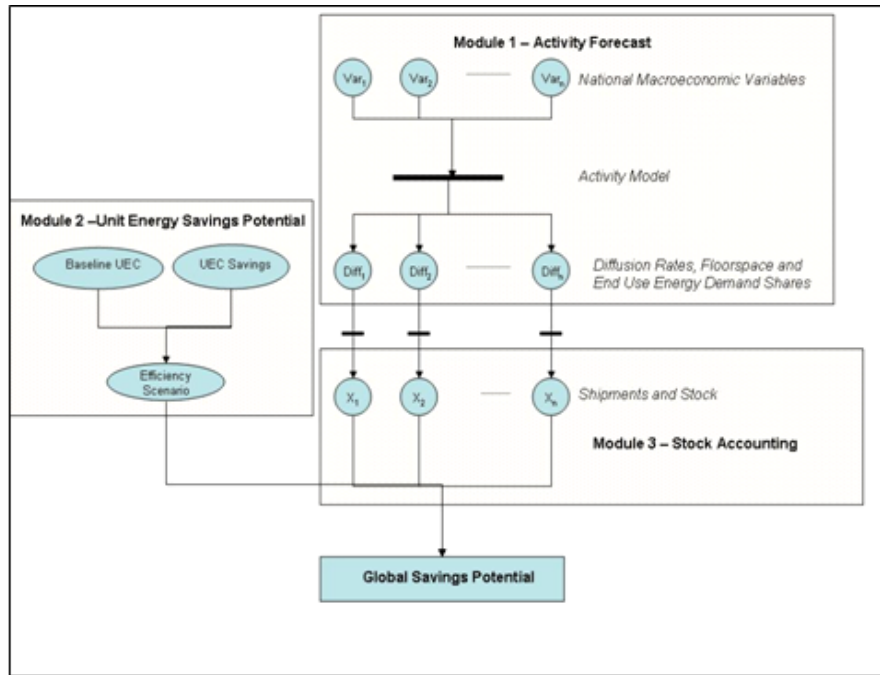
BUENAS Methodology

BUENAS is an analytical framework developed at LBNL that has been used in several previous studies: [7],[10],[11],[12] and [13].

The strategy of the model is to construct the analysis in a modular way. The first module models demand for energy services (*activity*) at the end use level, while a second considers the final energy used to provide those services in the base case, and builds a high-efficiency scenario based on meeting equipment efficiency targets by a specified year. A third module tracks market penetration and stock turnover for efficient products. Finally, these three components are brought together, and savings are calculated as the difference in consumption and emissions in the high-efficiency scenario versus the base case. The analysis framework is shown below in Figure 1.

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Figure 1 Bottom- Up Energy Analysis (BUENAS) Flowchart



Diffusion Model

The first step in modeling energy demand is to forecast *activity*. To do so, the relation between household income and appliances ownership is determined. Data on the number of appliances per 100 households are available from [16] and [17] from 1990 to 2007. The ownership data and household income are disaggregated into urban and rural regions, which allows for modeling those two regions separately.

A logistic function¹ describes the penetration of appliances in the households, as given by the following equation:

$$Diff(year) = \frac{\alpha}{1 + \gamma \exp(\beta \times I(year))}$$

All parameters are determined separately for urban and rural households. The parameter α is the maximum diffusion per 100 households, which may be greater than 100. For rural households we defined α as the diffusion in urban household for the same income level. $I(year)$ is the average per household income in *year* and γ and β are scale parameters. These parameters are determined using regression analysis by comparing historical diffusion rates to average per household income in each year. Income and diffusion rates disaggregated into urban and rural are found in the *China Statistical Yearbook 2005* [16] and *2008* [17].

In the case of air conditioners in urban households, a dummy variable for the year was added to the logistic diffusion equation resulting in the following formula:

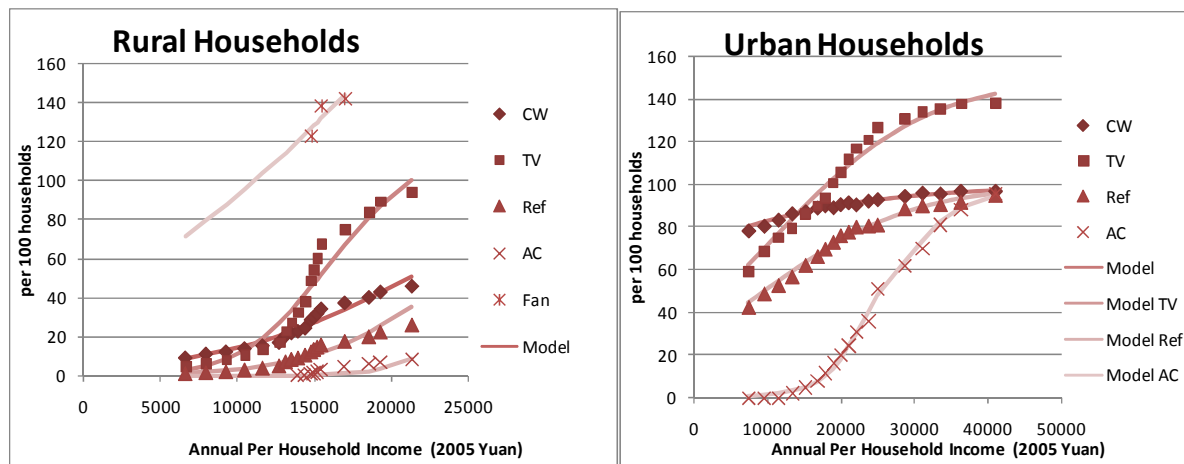
$$Diff(year) = \frac{\alpha}{1 + \gamma \exp(\beta_{year} \times year + \beta_{Inc} \times I(year))}$$

¹ Because of its S-shape, the logistic function is often used in consumer choice models

This additional time dependency accounts for the rapid diffusion of this technology in the urban sector over the past 15 years, as air conditioning became more available and affordable.

Figure 2 shows the historical diffusion data as a function of household income, and the resulting model fits.

Figure 2 – Appliance diffusion as a function of household income – (historical)



Fan diffusion data were not available for urban households, so diffusion rates were assumed to follow the same income dependency as for rural households. Since no data were available for the number of lighting fixtures per household, we relied on a model developed for another study [10] that relates the number of fixtures per household in different countries to national incomes. The breakdown by type of lamp is then provided by IEA as follows [5]:

Table 1– Lamp Type breakdown in 2000:

Lighting Type	Incandescent	Fluorescent	CFL
Percentage in stock	0.57	0.20	0.23

Standby power was also modeled using global data on total standby wattage per household [10]. Parameters from the China-specific model along with the global model are gathered in Tables 2 and 3.

Table 2 – Appliance diffusion model parameters – urban households

End Use	α	$\ln \gamma$	β_{year}	β_{Inc}	R^2
Clothes Washer	100	-0.90		-6.64E-05	0.97
Color TV	150	1.06		-9.63E-05	0.96
Refrigerator	100	0.93		-9.76E-05	0.98
Air Conditioner	100	439.54	-0.22	-1.12E-04	0.99
Light Points	4000	1.85		-3.92E-05	0.74
Standby Power	1200	2.10		-4.01E-05	0.57
Fans	300	1.86		-1.05E-04	0.71

Table 3 – Appliance diffusion model parameters – rural households

End Use	α	$\ln \gamma$	$\beta \ln c$	R^2
Clothes Washer	Urban Diff	3.20	-1.61E-04	0.95
Color TV	Urban Diff	5.28	-3.62E-04	0.92
Refrigerator	Urban Diff	4.98	-2.26E-04	0.93
Air Conditioner	Urban Diff	9.52	-3.59E-04	0.80
Light Points	4000	1.85	-3.92E-05	0.74
Standby Power	1200	2.10	-4.01E-05	0.57
Fans	300	1.86	-1.05E-04	0.71

Once the relationship between appliance ownership and income is established, diffusion rates $Diff(year)$ are forecast to 2050 according to GDP per capita growth [3]. The forecast of household size in urban and rural areas provided by ERI [3] are shown in Figure 3. The resulting diffusion rates are shown in Figure 4.

Figure 3 – Annual per household Income in 2005 Yuan

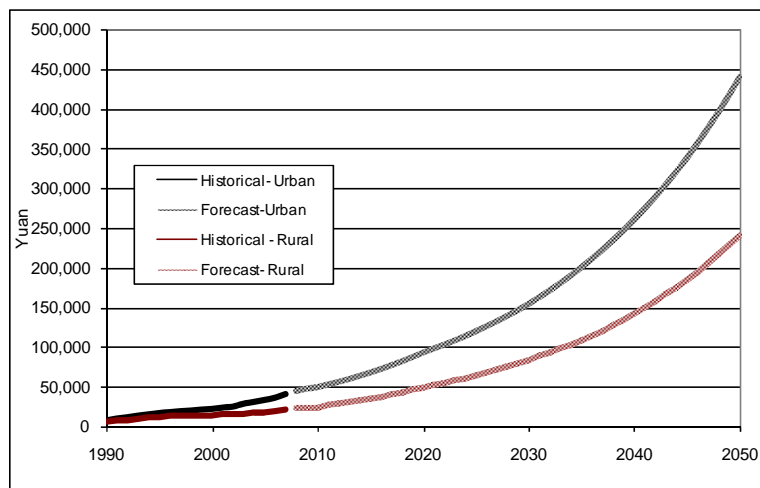
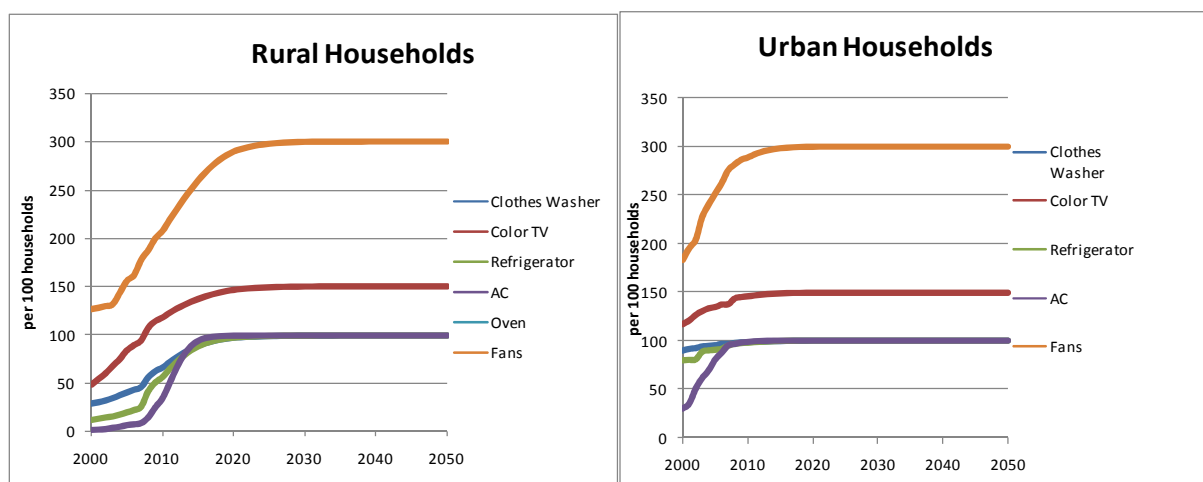


Figure 4 – Number of Appliances per 100 Households: Historical Data and Projections to 2050



Unit Energy Consumption Baseline and Efficiency Scenarios

The following section describes the methods and assumptions for determining the average unit energy consumption (UEC) for each end use under 3 defined scenarios. The first “frozen efficiency” scenario assumes no efficiency improvements from the base year. The high-efficiency scenario represents achievement of realistic efficiency targets through aggressive implementation of market transformation policies, such as minimum efficiency performance standards (MEPS), or labeling programs. An intermediate Business As Usual (BAU) case was created assuming that, in the absence of aggressive policies one third of the high-efficiency case improvement will be achieved as a result of market-driven technology improvement. The BAU case and the frozen efficiency case are the same until the first standard comes into effect in 2010. The efficiency case is modeled as a set of successive MEPS coming into effect in three tiers, to be implemented in 2010, 2020 and 2030. In this scenario, all new equipment installed in households after the implementation year will meet the corresponding efficiency target. The corresponding efficiency case assumptions for each end use are detailed in the following sections.

Air Conditioners

The baseline is the current 2005 standard at 2.3 EER. A more stringent “reach” standard will come into effect in 2009 with an EER of 3.2. No further improvement is expected until 2020, at which point we assume a new standard at 4 EER by 2020, and 6 EER by 2030 [14]. We use the UEC provided in [20] to which we apply a growth rate determined in [10] to account for bigger units and increased conditioned space as income rises. The relation has been determined as follows:

$$UEC (year) = 0.029 * Income (year) + 1.44 * CDD - 967$$

In this equation, *Income(year)* is the annual household income in 2000\$ and CDD the number of cooling degree days in China (constant).

Refrigerators

China has already implemented a series of standards for refrigerators in 1999, 2003 and 2007 [4]. No further improvement is assumed until 2020. Refrigerators UEC has been derived from size and efficiency market shares described in [20]. By 2020 we assume the European Level of A++ is reached. The following table summarizes the resulting new equipment UEC for urban and rural households.

Table 4 Refrigerator UEC Summary:

Refrigerator UEC (kWh)	Rural	Urban
2000	412	501
2007	260	411
2020	188	215

Washing Machines

Only impeller type washing machines are considered in this analysis. The 2004 criteria was set to 0.032 kWh/kg/cycle, which gives an annual electricity consumption of 12kWh assuming 2.5 kg per load and 250 cycles per year per washer. It has been estimated in [8] that this consumption could go down to 6kWh per year, which is what has been used for the 2010 target.

Televisions

For televisions, we model only color televisions, since efficiency programs will likely only cover new products. The consumption of a TV is mainly dependent on the size and the image technology. We consider three types of TVs: CRT, LCD and Plasma TVs, with respectively an average power of 70, 180 and 300W. We then take in account the shift from traditional CRT televisions to more consuming plasma and LCD screens as described in [10]. The resulting UEC has been parameterized as:

$$UEC = UEC_{max} / (1 + \exp(171.5) * \exp(-0.0855 * year))$$

Where UEC_{max} is assumed to be 300kWh.

Efficiency scenarios are based on technical improvement on LCD and plasma screens found in [1]: 34% improvement on LCD, 36% on Plasma TVs by 2010. The improvement on standby power consumption is taken in account in the standby category.

Lighting

In the high efficiency scenario, we assume that incandescent bulbs are gradually replaced by CFLs at a rate of 1% per year. Recalling Table 1, this means that 23% of lighting will be CFLs by 2010, 33% by 2020, etc. For fluorescent lamps we assume that ballast losses will be reduced by switching from electromagnetic ballasts to low loss electromagnetic ballasts in 2010 and electronic ballasts by 2020. Wattages used in the analysis are summarized in Table 5:

Table 5- Lighting Wattage by Category [2]

	2000	2010	2020
Fluorescent Lamps	44 W	41.4 W	34.6 W
Incandescent Lamps	60W	60W	60W
CFL	15W	15W	15W

We then calculate consumption from wattage by using an average hours of use per day which was found to be 2.3 hours averaged over several developing countries for which data were available [10].

Standby Power

We assume the average base case standby wattage to be 5W per product. Since this particular end use is active 24h hours a day, the base case UEC is a straightforward calculation. For a maximum 60W standby power (which represents 12 devices consuming a standby power of 5W-see table 2 and 3), the annual consumption is 512 kWh, given by

$$UEC(kWh) = 60W \times 24h \times 365 \times 10^{-3} = 512kWh$$

High efficiency scenarios are given simply as 3W and 1W standby power per device, values that appear commonly in proposed standards or endorsement levels.

Fans

The baseline UEC for fans has been estimated to 10 kWh from data given in China Statistical Yearbook 2002 [15]. Potential fan efficiency improvement is based on studies in the U.S. targeting ceiling fans. U.S. ceiling fans often are fitted with lighting fixtures, and both the mechanical and lighting energy are considered for efficiency by the USEPA Energy Star program. For our study, we consider only mechanical efficiency. Energy Star is 18% more efficient than the baseline, and the best technology available is 39%. Those will be the targets for 2010 and 2020 [19].

Water Heating and Space Heating

Water heater intensities and electric equipment market shares were taken from [20] and projected to 2050 using constant growth rates. Space heating intensities per region (North and Transition) were also taken from that study, along with conditioned floor space and equipment market shares [20]. Those components were projected after 2020 under various assumptions, mostly following growth rates before 2020.

An efficiency scenario was built for electric storage water heaters and heat pumps as shown in table 6. Resistance electric heating is assumed to have an efficiency of 100% (assuming all Joule heat enters the space to be conditioned). By 2030, we assume that electric storage tank water heaters will be replaced with heat pump water heaters (efficiency of 250%).

Table 6 Efficiency Levels for Electric Water Heaters and Heat Pumps

End Use	Efficiency Level				Source	Assumption
	Base	2010	2020	2030		
Elec WH	0.76	0.83	0.88	2.5	[18]	Based on European Labelling Levels: Level G to Level E in 2010, and Level C in 2020, HP by 2030
HP	1.0	2.0	3.0	4.0	[20]	Baseline of 1.0 scales up to 4 by 2030

Shipments and Stock UEC Calculation

Calculation of unit equipment sales (shipments) and stock turnover is essential in understanding the rate at which products enter the household population and thus impact the overall energy consumption. This shipments rate impacts both the base case and efficiency scenarios. After the standard is passed, savings come from the households acquiring the appliances for the first time but also from replacement of older products by efficient products as they are retired.

Shipments are calculated as the sum of the first purchases and replacements. The first purchases are the increase in appliance stock from one year to the next, where stock is the product of number of households and the diffusion rate. Replacements are calculated based on the age of the appliances in the stock and a retirement function that gives the percentage of surviving appliances in a given vintage. The incremental retirement function is a normal distribution around the average lifetime. We assume an average lifetime of 15 years for all appliances, except for incandescent lamps (1 year) and fluorescent tubes and CFLs (5 years).

Results and Conclusion

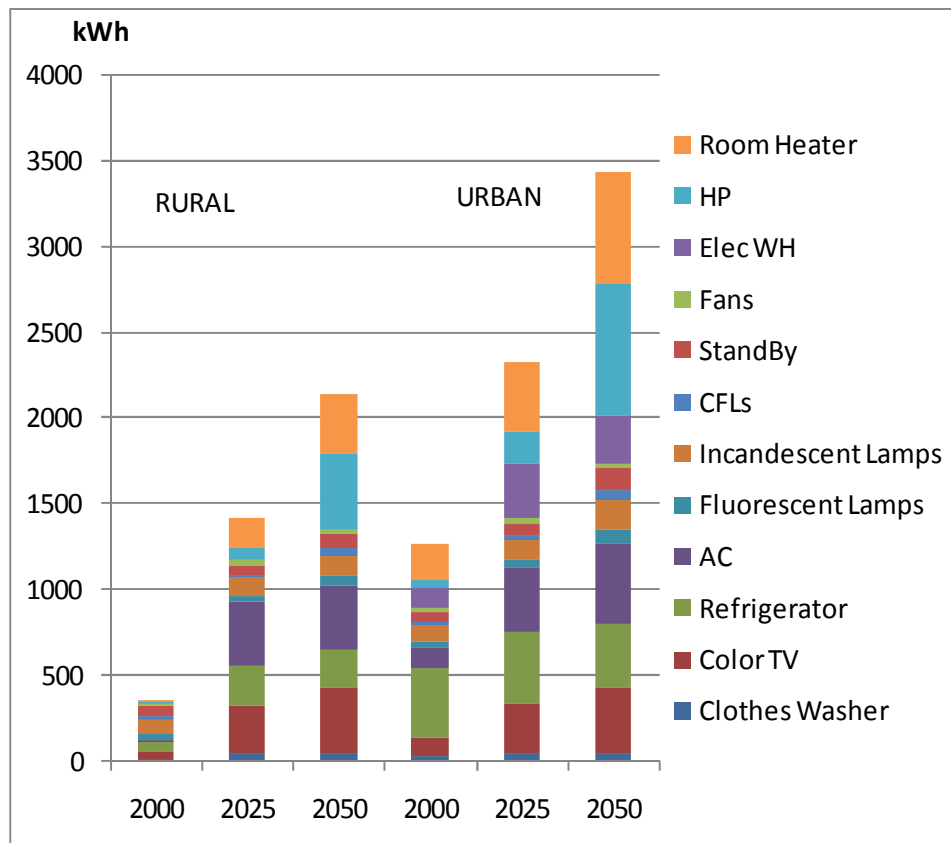
In the last step of the calculation, shipment and stock accounting are combined with unit efficiency scenarios to calculate average marginal and stock UEC. Finally, the equation of residential energy consumption is given by:

$$E(year) = \sum_{r,c} HH_{r,c}(year) \times SH_{r,c}(year) + HH_r(year) \times \left(\sum_i Diff_r(year)_i \times UEC_i(year) \right)$$

Households are broken into rural/urban location (index r), and climate zone (index c). SH is the average space heating energy consumption per household, which varies by climate zone and location. $UEC_i(year)$ is the average unit energy consumption in the stock of the appliance i in the considered efficiency scenario (Frozen, BAU and S&L).

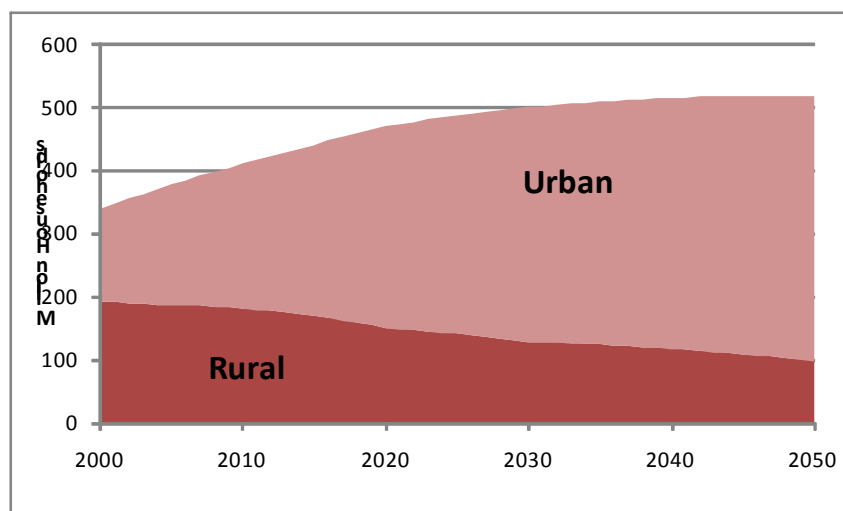
One interesting metric to look at is electricity consumption at the household level. Figure 5 shows the modeled consumption in 2000 and 2050 in the BAU case for both urban and rural households. The results show that the annual electricity growth rate in rural households is 3.6%, compared to the growth rate in urban households, where it is 2.3% per year.

Figure 5 – Modeled Annual per household Consumption



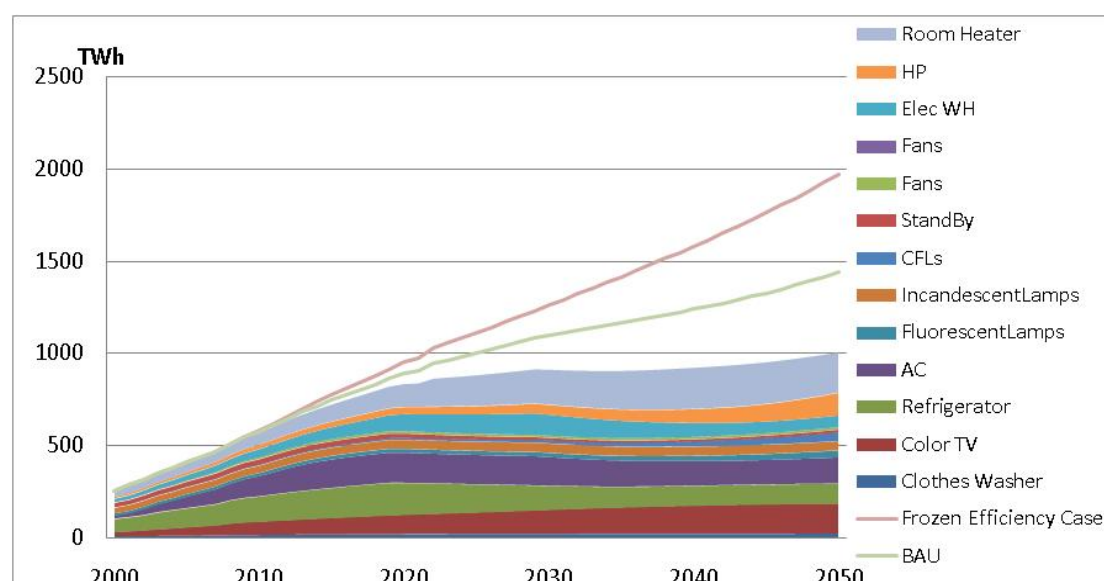
The following figure shows the number of households in each area urban and rural, which is a main driver in national energy consumption [3].

Figure 6 Number of households in urban and rural areas



The following figure shows electricity consumption in China by end use in the three scenarios. By 2050, efficiency programs considered here can save 750 TWh each year compared to the BAU case and 1150 TWh compared to the frozen efficiency case.

Figure 7 – China Residential Electricity Consumption 2000-2050



The following table shows the electricity consumption annual growth rates for the three scenarios for every decade, since standards levels are applied every 10 years. The growth rate between 2000 and 2010 is by far the largest since it's when most of the households get access to high intensity end uses for the first time.

Table 7 Annual Consumption Growth Rate in the three scenarios

Annual Growth Rate	2000-2010	2010-2020	2020-2030	2030-2040	2040-2050	2000-2050
Frozen Efficiency	8.6%	5.0%	2.9%	2.3%	2.2%	4.2%
BAU	8.5%	4.4%	2.1%	1.2%	1.5%	3.5%
S&L	8.4%	3.8%	0.9%	0.1%	0.9%	2.8%

Conclusion

This bottom-up analysis of residential electricity scenarios in China provides important insight into the prospects of significantly reducing demand growth in several ways. First, it identifies the particular end uses which will drive demand as households acquire more appliances. It also has an advantage over more macro estimates in that it models saturation effects (households are unlikely to have more than one refrigerator or washing machine, etc.). In addition, savings estimates are based on a realistic set of policy actions, which gradually bring the appliance market up to international best practices. These efficiency targets are in turn based on real-world examples from existing efficiency programs around the world. Implementation of such policies therefore becomes a question of political will and effectiveness of implementation, rather than the development of new technologies or reduction of economic barriers.

Further work is undergoing to determine the effect of building codes on heating and cooling loads, and whether this type of regulation without reform of the district heating system is meaningful, since currently many households do not have control over the amount of heat entering the residence.

Several important conclusions can be drawn from the results. Most obviously, residential electricity consumption in China is currently growing extremely rapidly. This is not a surprise due to the recent history of extremely high economic growth. The analysis confirms that this demand is driven by a rapid uptake in appliances, resulting in near saturation levels for some appliances in the urban sector. In the near future, this trend toward saturation will be nearly complete in urban households, and rural

households will also become users of most major appliances. This effect, in combination with continued urbanization mean that demand growth is likely to be strong over the next year. As appliance diffusion reaches saturation, however, growth will slow.

In the high-efficiency case, the next ten years will still experience high demand growth, because of the time delay in penetration of the stock by high-efficiency equipment. After that, however, efficiency programs will start to have a significant impact on growth. A system of ratcheted targets will maintain this impact, in spite of the continued trends toward urbanization reaching best-practice levels by 2030, if not already reached by 2020. In this scenario, residential electricity consumption will continue to rise significantly till 2020, after which it will be largely stable for several decades. By 2050 efficiency programs could bring demand by 60% relative to business as usual.

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